Real-time Coupling of Multi-domain Representational and Analytical Building Object Models via Homology-based Mapping

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1. Introduction

Ideally, the process of building design should involve multi-domain analysis of building performance, including energy use, thermal comfort, acoustics, lighting, etc. Over the past two decades numerous computational simulation tools have been developed to facilitate performance evaluation of buildings in each of these domains. This has enhanced performance prediction capability in at least three critical ways: buildings could be modeled with a greater level of detail, sophisticated performance modeling algorithms could be incorporated within simulation programs, and detailed performance data could be obtained from the programs.

However, computational performance simulation tools are mostly used only by domain-specific experts, and are not widely applied in the building design practice. Many explanations have been suggested, indicating contributing factors such as material and time implications, problematic user-interfaces, poor integration with general CAD systems, and the absence of „active“ design support. This paper specifically focuses on the „integration problem“ i.e. the quest for effective containment of performance simulation in the general computer-aided design environment.

In the first part of the paper, we present an overview of the nature and parameters of the integration problem vis-à-vis concurrent building performance simulation, and briefly review some approaches that have been taken to address it. In the second part, we present an approach that utilizes homology-based mapping to couple simulation models and the general building representation, using as a demonstrative example the coupling of a nodal energy simulation model within a prototypical multi-aspect design and simulation environment. We conclude with some remarks on the extensibility of this approach to other domains.

2. „The Integration Problem“

The main difficulty in integrating performance analysis tools with CAD tools is due to the differences between the building representations used for simulation and the building representation in typical CAD tools. Simulation tools use representations that correspond to their particular „view“ of the building - one which reflects the underlying mathematical methods of the simulation technique. For instance, a room acoustic simulation tool that relies on a sound-particle distribution techniques requires a representation that includes spatial volumes with bounding and internal surfaces that can be discretized. Such a representation may not map directly to the building representation in a common computer-aided architectural drafting tool which is typically devoid of spatial enclosure information and/or surface attribute information. As a result of this, a designer will typically need to input the building data separately for each domain application - a process that is time-consuming, cumbersome, and error-prone (cp. figure 1).

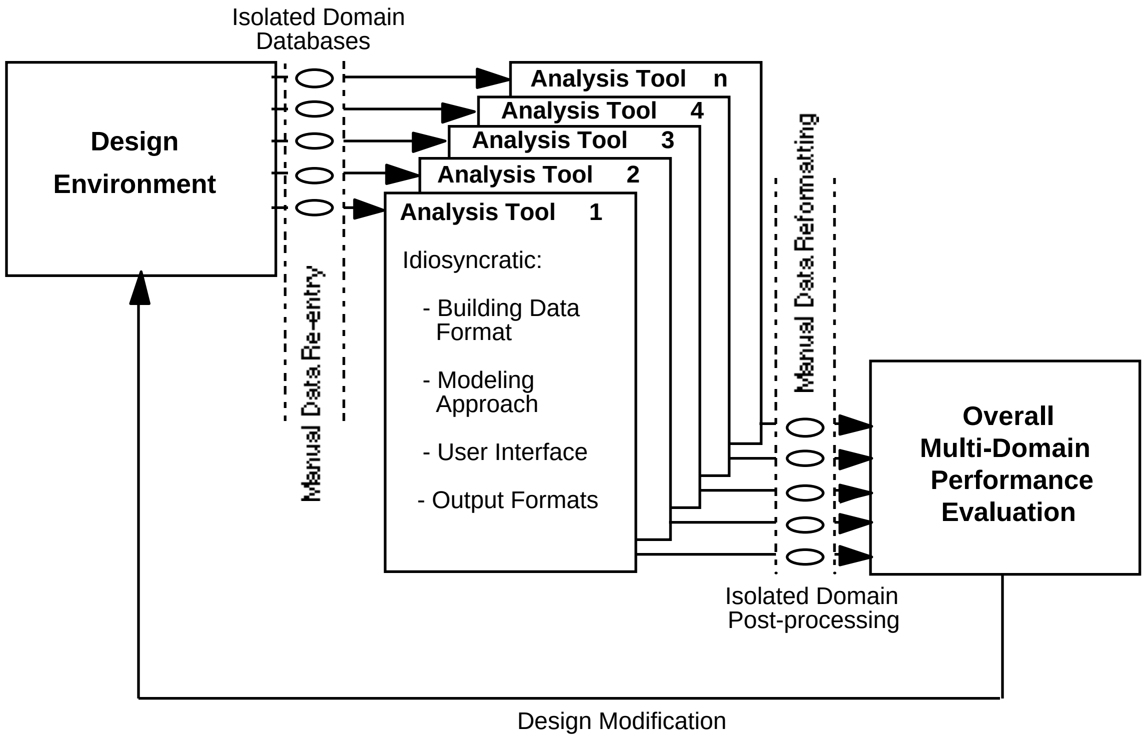

Figure 1: Conceptual illustration of the „Integration Problem“ in multi-aspect building performance simulation

The integration of building design and simulation tools has been the subject of many research efforts, which vary widely in their approach to overcoming the semantic gap between the building representation in simulation tools and the representation in CAD tools, and also vary in the types of the tools that they integrate (simplified vs. detailed, existing vs. new). For example, in COMBINE (Augenbroe 1992), a common data model and application specific translators are used to support communication between distributed applications (Mellotte et al. 1995). This effort was mainly geared towards multiple, geographically distributed users, and involved fairly sophisticated applications such as ESP for energy simulation. At the other end of the spectrum, there are single-user tools like Softdesk Energy, which incorporates a simplified energy analysis algorithm within AutoCAD (Softdesk 1996). Despite such efforts, the effective integration of detailed simulation tools and design environments remains an open research question, particularly because of the semantic limitations of existing CAD tools and the idiosyncratic informational requirements and formats of existing simulation tools.

Given this background, we suggest that many difficulties in overcoming certain obstacles in solving the integration problem may be largely attributed to the "non-integrated" informational context and problem solving methodologies of the professional communities involved. The architectural CAD system designer with a software engineering or general architectural background has usually treated evaluation routines as isolated (black-box type) application modules without questioning or investigating their inherent computational logic and underlying data structures. As a result, in many instances, the integration problem has been reduced to the technicalities of module interfaces, translational overlays, and data transfer mechanisms. On the other side, the researchers dealing with the development of computational performance simulation routines may well have reinforced this reductionist approach by viewing CAD systems as service utilities (i.e. glorified user interfaces) for their simulation modules that in many instances have not gone beyond mere algorithmic routines (Mahdavi and Mathew 1995).

This argument implies that more elegant and effective solutions for the integration problem are likely to be found if the potentially existing structural homologies in general (configurational) and domain-specific (technical) building representations are exploited.

3. Real-time Coupling via Homology-based Mapping

The desired integration of detailed simulation methods and CAD systems is complicated by the fact that the building representation needed for detailed simulation methods does not adequately match the representation used in commercially available CAD systems. For example, in the case of energy simulation, detailed simulation methods require the definition of spaces and zones, and not just bounding surfaces, as would be the case with single-zone steady state simulation programs. Yet almost all currently available commercial CAD systems rely on building representations that do not include spaces. A space-based CAD system, however, would provide a representation that is practically homologous to the thermal representation needed for a detailed heat-balance-based energy simulation tool, and thereby could facilitate integration. Here, the term „homologous“ is used to mean that the two representations have information structured in a manner such that they can be derived from each other without having to interpret semantics (e.g. geometry interpretation).

The use of homology-based mapping has been demonstrated within SEMPER - a multi-aspect design and simulation environment which has various performance simulation modules linked with a prototypical object-oriented, space-based design environment (Mahdavi 1996, Mahdavi et al. 1996). Figure 2 indicates the architecture of SEMPER, the components of which include *a)* a shared object model of the building; *b)* various simulation modules (domain applications); *c)* a database; and *d)* a user interface. With this software architecture, direct links between individual domain applications are avoided. Instead, the links occur at the object model level through mechanisms such as derived values, allowing for individual applications to be developed fairly independently, while still communicating in an effective manner. In SEMPER, the traditional „CAD system“ merely becomes part of the graphical user interface.

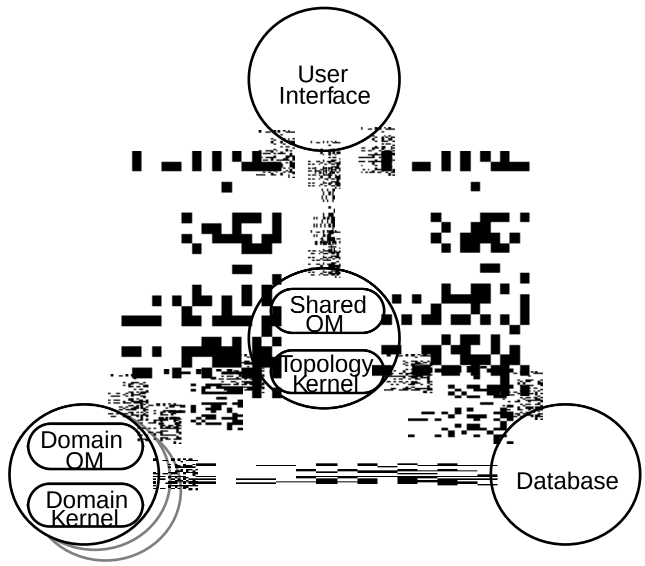

Figure 2: The architecture of SEMPER

The homology-based mapping from the shared building representation to that of a specific domain can be illustrated using an example from the energy simulation domain. The shared building representation embodies topological information and it therefore has „knowledge“ of architectural spaces and their relationships (adjacencies, etc.). SEMPER incorporates a heat balance-based nodal energy simulation module called NODEM (Mahdavi and Mathew 1995, Mathew 1996), which utilizes a spatial representation consisting of spatial units (cells). Each cell is thermally represented by a node that defines a finite control volume for heat-balance calculations.

NODEM's underlying spatial representation is configurationally homologous to the space-based representation of the building in the shared object model, and can therefore be directly derived from it (figure 3). Furthermore, the thermal node configuration is automatically updated based on design modification in the shared object model without any additional user intervention (figure 4). To increase the operational efficiency of the system, a 3-dimensional grid for discretizing the spaces into cells is adopted, which also serves as a building geometry input framework. Spaces are agglomerations of cells, as are HVAC zones. This cell-based discretization allows for efficient derivation and solution of the system of equations. As the design progresses, the resolution of this grid may increase, resulting in a more detailed analysis.

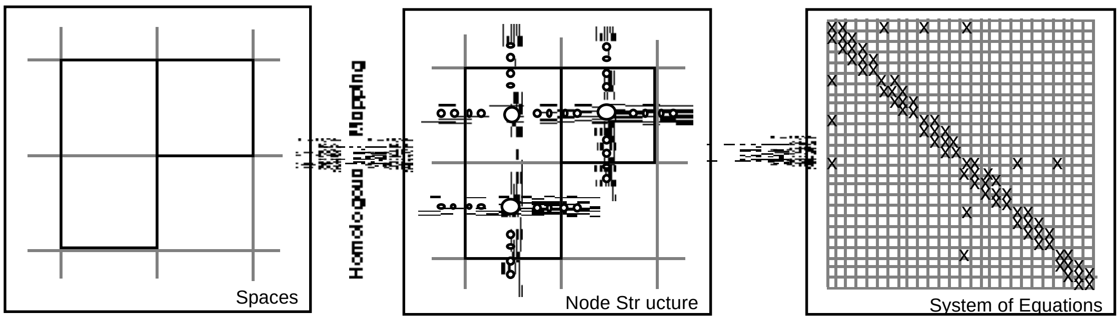

Figure 3: Homology-based mapping from space-based CAD system to nodal energy model and system of heat-balance equations

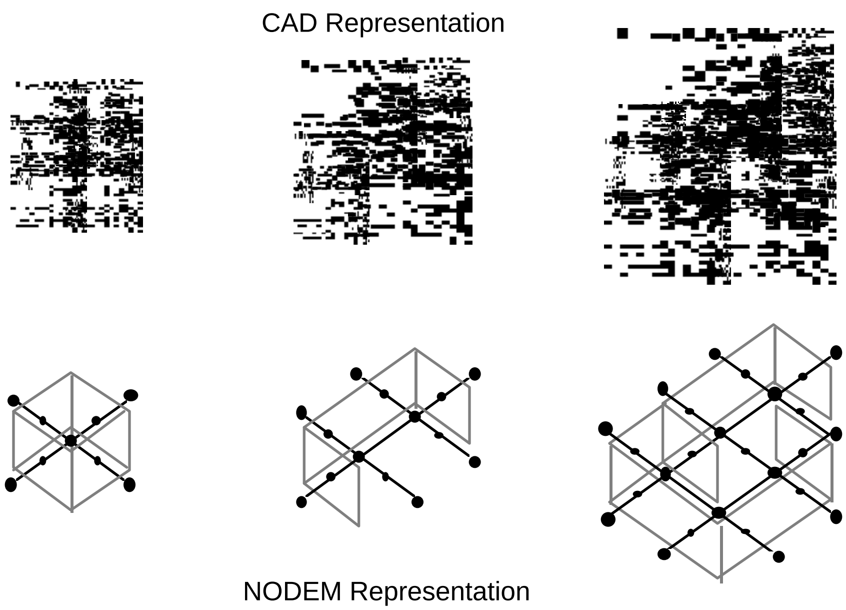

Figure 4: Automated updating of nodal model based on changes in CAD model

The discretization of the spaces into cells, the creation of the homologous node structure and the system of equations for hourly simulation is completely automated from the shared building representation. This real-time coupling of representational and analytical building object models thus provides „on-line“ simulation feed-back to the user while eliminating the need for explicit definition and updating of the underlying thermal model. Furthermore, this is done without having to use complex application-specific translators or communication frameworks.

4. Concluding Remarks

We have suggested that the integration of design and simulation tools can be more effectively facilitated if the potentially existing structural homologies in their respective building representations are exploited. We demonstrated the use of homology-based mapping to integrate a nodal energy simulation tool (NODEM) within a space-based design environment (SEMPER). Current work suggests that this approach can be extended to multiple performance simulation domains, particularly if a space-based design representation is used. Consequently, in SEMPER, homology-based mapping is also being used to integrate a hybrid multi-zone and CFD air flow model, a component-based HVAC model, a sound-particle-based acoustic simulation module, and an Eco-balance-based life-cycle-analysis module.

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